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Initial experiments to explore ways to modify the key aspects of the turbulence production mechanism were made. The proposed phased momentum bursts proved too difficult for us to quantify. When applied, changes were visually observed to occur, but the changes that occurred always seemed to result in different evolutions from instant to instant even though the same perturbation was applied, and thus defied quantification. Therefore, we took a different approach, and determined in a statistical sense what the magnitude and the time scale of a momentum perturbation should be if we are going to precisely alter the essential coherent motions. We have found these scales by constructing a complete structural model of the turbulent boundary layer (Proc. Roy. Soc. Lond. A 336, 103-129, 1991), and by showing that it properly scales the intensities and Reynolds stresses. This scaling allows us to predict intensities and Reynolds stress magnitudes. From the point of view of control, it tells us, on a statistical basis, how much momentum to use in a control scheme, and for how long to apply it. for any Reynolds number and position in the layer.

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## 1. Overview

This work has resulted in a number of publications that detail a complete model of the coherent motions and their interactions. Initial experiments to explore ways to modify the key aspects of the turbulence production mechanism were made. We attempted to make change in the evolution of isolated simulated features as well as in the fully turbulent layer.

Unfortunately the understanding of the difficulties expressed by the statement in the proposal "we do not expect that optimal controls will be discovered", were underestimate. The problem of quantifying the sensitivity of specific turbulence mechanisms to controls by making direct, fixed, local modifications turns out to be much more difficult than anticipated. To make progress with this approach, which we now feel will only work on simulations, one needs significantly more resources. We knew this going in, and therefore focused on the pocket vortex as the most likely mechanism that controls could be applied to. Using the structural picture of Falco (see 1991 Proc Roy Soc., and earlier references given below), we focused on reducing the spreading rate of this vortex.

The two mechanisms that are operative and that contribute to the spreading of the pocket vortex are viscous shear, and inviscid stretching (due to the presence of the wall). We attempted to change both the shear and the strength of the 'mirror image' effect in the experiments performed.

The proposed phased momentum bursts proved too difficult for us to implement. The bottom line was that for all three 'stages' of the proposed program -- the simulation, the water tunnel LIPA runs, and the wind tunnel boundary layer vorticity probe studies -- changes were visually observed to occur (often with the smallest perturbations we could generate), but the changes that occurred always seemed to result in different evolutions from instant to instant even though the same perturbation was applied.<sup>1</sup> This frustrated our attempts to quantify the changes. With the scatter in the response so large, we would need to analyze literally thousands of LIPA grids. Since during this time period we were evaluating grids by hand, this was simply not possible to do. In addition, during the course of doing this we discovered from

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<sup>1</sup>With hindsight this is not so surprising since the perturbations are applied to a specific location, but the events to be modified pass that location with random positioning in the turbulent boundary layer. However, in the ring/wall simulations we had reasonable hope to do better.



our wind tunnel experiments that the length of hot-wire record necessary to get convergence of vorticity statistics in an unperturbed boundary layer was so long that convergence was poor in a natural boundary layer (JFM 219, 1990). The 1/2 million data points that we discovered were needed for 5% accuracy effectively made the use of LIPA for this purpose unrealistic. (It should be noted that this signal length was 100 times longer than previously reported for free shear layers.) Thus, the additional significantly greater variance observed when modifications were introduced would also make it essentially impossible to see the effect of the controls -- even in air. Thus, the only way we could follow this line of attack was with a drag balance, which we did not have.

This understanding led to a different approach. We went back to flow visualization in the fully turbulent boundary layer in air, and applied some controls two-dimensionally. This has three advantages. We get area information, we get Lagrangian information and we apply the perturbation in a similar way to a large number of pocket events. The controls applied were attempts to address both the viscous and the inviscid mechanisms that lead to vortex stretching. Small separated regions of the order of the viscous sublayer in thickness and of the order of hundreds of viscous lengths long were made using micro rearward facing steps. Flow visualization of the formation of pockets was studied. Results (the Thesis of S.-C. Yoo, see below) showed that the number of pockets has decreased significantly.

Perhaps the most successful inroads we have made into understanding how to determine to sensitivity of the turbulent boundary layer production mechanisms is summarized by the scaling shown in figure 1 ( taken from the proceedings of the Royal Soc Lond A, 336 see below). I asked the question, "statistically what should the momentum and time scales of a momentum perturbation be if I am going to precisely alter the essential coherent motions? It would have to be the characteristic momentum and time scales of these motions. If I could find those scales, and if they are the important Reynolds stress producing scales, then boundary layer statistics such as the turbulence intensities and Reynolds stresses would show similarity (i.e. collapse) when normalized by them. Figure 1 shows that we have found those scales (in the inner region). This has been done, for the first time, using coherent motion ideas. The results are very convincing. We now have a handle on these quantities. This collapse allows us to predict intensities and Reynolds stress magnitudes. From the point of view of control we now know, on a statistical basis, how much momentum to use in a control scheme, and for how long to apply it. for any Reynolds number and position in the layer. An experimental program could be initiated again using these quantities, but it would have to be applied over a large enough area to get a statistical result ( basically it must be done on a large



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plate attached to a drag balance). Furthermore, using this modeling we can now study some aspects of the sensitivity of the controls analytically. For example, if we make the Typical Eddy scale smaller, say, by 5%, or the Typical Eddy faster than nature makes it in a normal boundary layer at a given Reynolds number, we can determine how much less Reynolds stress we will have.

We have gone a step further. The very recent PhD work of K. Pan (March 1992), which is an essential piece of information, especially if control is to be handled statistically, finally was completed in March 1992. It provides us with statistics on the scales and probability of phase relationships of the Typical Eddies, the long streaks and the pockets (which give us information on both the pocket vortices and primary hairpin vortices). If an area sensing array could be fabricated, correctly phased trains of input could be introduced, and statistically we could distribute momentum slugs of the right magnitude and duration to have a statistical match with the coherent structures. The results of tweaking the 'knobs' of this analog computer would be fascinating.

## **2. Publications derived from this work**

"Visualization of inner/outer layer interactions producing turbulence near walls". In 'Flow Visualization IV', ed. C. Veret, pg. 327-332, 1987.

"A coherent structure model of the turbulent boundary layer". Proc. Workshop on Turbulent Wall Layers, ed. R. Panton and D. Bogard, 1987.

"What happens to the large eddies when net drag reduction is achieved by outer flow manipulators?", (with N. Rashidnia). Proc. of Symposium on Turbulent Drag Reduction by Passive Means, London 1987.

"Measurement of two-dimensional fluid dynamic quantities using a photochromic grid tracing technique", (with C.C.Chu), SPIE, Vol. 814, Photomechanics. 1987.

"Two-dimensional Fluid Dynamic Measurements Using LIPA" Proc Image Processing and Analysis Workshop", ed Brodkey and Guezennec, Ohio State Univ. 1988.

"Vortex ring/viscous wall layer interaction model of the turbulence production process near walls", (with C. C. Chu). Exp. in Fluids 6 p. 305-315, 1988.

"The Circulation of an airfoil starting vortex obtained from instantaneous vorticity measurements over an area", (with C. C. Chu, M. H. Hetherington, C. P. Gendrich). AIAA Paper 88-3620, in Proc. 1st National Congress on Fluid Mechanics, Cincinnati, 1988.

"The Turbulence Burst Detection Algorithm of Z. Zaric", (with C. P. Gendrich) in Turbulence Near Walls, ed. S. J. Kline, Hemisphere Press, N.Y. 1989.

"Correlation of Outer and Passive Wall Region Manipulation with Boundary Layer Coherent Structure Dynamics and Suggestions for Improved Devices". AIAA Paper 89-1026, 1989.

"Production of Turbulence in Boundary Layers", (with J. C. Klewicki and K. Pan) in the Proceeding of the 7th Turbulent Shear Flows Symposium, Stanford Univ., August, 1989.

"Vorticity Field Measurements Using Laser Induced Photochemical Anemometry (LIPA) (with C. P. Gendrich and C. C. Chu). in the Proceeding of the 7th Turbulent Shear Flows Symposium, Stanford Univ., August, 1989.

"Production of Turbulence in Boundary Layers and Modification of the Near Wall Region", (With J. C. Klewicki and K. Pan) in *Structure of Turbulence and Drag Reduction*, ed. A. Gyr Springer-Verlag. pp.59-68, 1990.

"On Accurately Measuring Statistics Associated With Small Scale Structure in Turbulent Boundary Layers Using Hot-Wire Probes (with J. Klewicki), *J. Fluid Mech.* 219. 119-142 1990.

On the sign of the instantaneous spanwise vorticity component in the near wall region of turbulent boundary layers, accepted for publication in *Physics of Fluids*.

"A coherent structure model of the turbulent boundary layer and its ability to predict Reynolds number dependence". *Phil Trans Royal Soc. Lond. A* 336, 103-129, 1991.

#### **Papers still in the publication process**

"On the Reynolds Number Dependence of Turbulence Statistics in Boundary Layers, submitted to *Journal of Fluid Mechanics*.

"Reynolds Stress Transport in Turbulent Boundary Layers", to be submitted to *Journal of Fluid Mechanics*.

"Organized vortical motions in the outer region of turbulent boundary layers", submitted to *Physics of Fluids*.

#### **Papers which have only had their ABSTRACTS published:**

"Instantaneous vorticity measurements over an area in unsteady and turbulent flows" (with C. C. Chu). *Bull. Am. Phy. Soc.*, Series II, Vol. 32, 1987.

"Two-point vorticity correlations in a turbulent boundary layer" (with J. Klewicki), *Bull. Am. Phy. Soc.*, Series II, Vol. 32, 1987, pg. 2061.

"The bursting process in turbulent boundary layers" (with C. C. Chu, K. Pan and J. Chang), *Bull. Am. Phy. Soc.*, Series II, Vol. 32, 1987, pg. 206

"The role of outer region manipulator wakes in turbulent boundary layer drag reduction" (with N. Rashidina), *Bull. Am. Phy. Soc.*, Series II, Vol. 32, pp. 2088, 1987.

"Turbulence Production in Boundary Layers" *Proc USC Turbulence Symposium*, ed. J. McMichaels, June 1988

**"Vorticity Field Measurements Using Photoexcited Chemicals", Proc USC Turbulence Symposium, ed J. McMichael, June 1988.**

**"Reynolds Number Effects on the Structure of Turbulence in Boundary Layers" (with J. C. Klewicki), Bull. Am. Phy. Soc., Series II, Vol. 33, 1988**

**"Eduction of Inner Region Turbulent Boundary Layer Structure for Two-Point Spanwise Vorticity and Reynolds Stress PDF's (with J. C. Klewicki and C. P. Gendrich), Bull. Am. Phy. Soc., Series II, Vol. 34, 1989, pp. 2300.**

**"Spanwise Vorticity Reorganization in the Near-Wall Region", (with J. C. Klewicki and C. P. Gendrich), Bull. Am. Phy. Soc., Series II, Vol. 34, 1989, pp. 2300.**

**"Comparison of Event Detection Schemes Used in both the Inner and Outer Regions of Turbulent Boundary Layers", (with C. P. Gendrich and J. C. Klewicki), Bull. Am. Phy. Soc., Series II, Vol. 34, 1989. pp. 2300.**

**'Structural Model of the turbulent boundary layer', NASA Turbulence symposium Aug 1990**

**'Reynolds Number Dependence of Vorticity Interactions in the Near-Wall Region. Part 1. The Interaction Region and Vorticity Reorientation'. Bulletin of the Am Phy Soc. pg 2293**

**'Reynolds Number Dependence of Vorticity Interactions in the Near Wall Region. Part II: Velocity Gradients Associated with the Sublayer Response'. Bull Am Phy Soc Series II pg 2293.**

**Need for High Reynolds Number Experiments Written discussion Symposium of Turbulence Structure and Control, Ohio State Univ. April 1-3 1991**

### **Lectures**

**"Overall model of the turbulent boundary layer" (invited) NASA Ames Research Center, April 1987.**

**"New results about the turbulence production mechanism" (invited), Princeton University, April 1987.**

**"Inner/outer layer interaction mechanisms in turbulent boundary layers" (invited series of lectures), Stanford Univ. 22-24 April 1987.**

**"What happens to the large eddies when the drag reduction is achieved by outer flow manipulators? Turbulent Drag Reduction by Passive Means, The Royal Aeronautical Society, London, 15 Sept. 1987.**

**"Measurement of two-dimensional fluid dynamic quantities using a photochromic grid tracing technique", Image Processing and Analysis Workshop, OSU, 16 Oct 1987.**

**"The bursting process in turbulent boundary layers DFDAPS Nov 23, 1987.**

**"Laser induced photochemical Anemometry", NASA Langley Research Center, (invited) Feb, 24, 1988.**

**"Field Measurements of velocity, instantaneous Reynolds stress and vorticity using laser induced photochemical anemometry (LIPA)", (Invited) Ford Motor Co. 11 April 1988.**

**"The photochromic technique for whole field velocity and vorticity measurements", (invited) NASA Lewis Research Center, 28 April 1988.**

**"Field measurements of fluid dynamic quantities using LIPA", (invited) Univ. of Ca., Davis, 2 May 1988.**

**"The Turbulence Burst Detection Algorithm of Z. Zaric", International Symp. on wall turbulence, Dubrovnik Yugoslavia, 20 May 1988.**

**"Turbulence Production in Boundary layers", USC Turbulence Symp. 28 June 1988.**

**Three invited lectures (University of Poitiers)**

**"The Structure of Turbulent Boundary Layers"**

**"Drag Reduction Mechanisms of Riblets and LEBU's"**

**"Laser Induced Photochemical Anemometry" Nov 28-1 Dec 1988.**

**"Drag reduction mechanisms of riblets and TAPPM's, (invited) University of Laussane, Switzerland, Oct 1988.**

**"A model of the wall region structure of the turbulent boundary layer, (invited) Univ. of Lyon, France, 17 Oct 1988.**

**"New aspects of the wall region structure of turbulent boundary layers", (invited) University of Toulouse, France, 19 Oct 1988.**

**"A comprehensive model of the turbulence production process in boundary layers, (invited) University of Marseille, Dec 6, 1988.**

**"The use of LIPA to measure the spatial structure in turbulent flows, and its application to the wall region of turbulent boundary layers, (invited) Cambridge Univ. England, Dec 12, 1988.**

**"The use of LIPA to measure simultaneous kinematic and thermal properties of high speed flows, (invited) NASA Langley Research Center, Feb 24, 1989.**

**"Correlation of outer and passive wall region manipulation with boundary layer coherent structure dynamics and suggestions for improved devices", AIAA Shear Flow Control Conference, March 17, 1989.**

**"Production of Turbulence in Boundary Layers and Modification of the Near Wall Region", IUTAM Symp on Turbulence, Zurich, July 28-Aug 1, 1989.**

**"Production of Turbulence in Boundary Layers", 7th Turbulent Shear Flows Symposium, Stanford Univ., August, 1989.**

**"Vorticity Field Measurements Using Laser Induced Photochemical Anemometry (LIPA)", 7th Turbulent Shear Flows Symposium, Stanford Univ., August, 1989.**

**"Use of LIPA in Automotive Applications", Symp on Automotive Fluid Mechanics, Ford Motor Co., Dearborn, MI. Oct 29, 1989.**

**"Eduction of Inner Region Turbulent Boundary Layer Structure from Two-Point Spanwise Vorticity and Reynolds Stress PDF's", APS DFD Nov 19, 1989.**

### **Thesis**

**Pan, Kue, "A Multiple-View Visual Stufy of the Inner/Outer Interactions of Coherent Motions in a Turbulent Boundary Layer," Ph D Thesis, Dept. Mech. Engr. Mich. State Univ. 1992.**

**Klewicki, J. C., On the Interaction Between the Inner and Outer Region Motions in Turbulent Boundary Layers", PhD Thesis, Dept. Mech. Engr. Mich. State Univ. 1989.**

**Gendrich, C., "On the Application and Interpretation of Coherent Motion Detectors", MS Thesis, Dept. Mech. Engr. Mich. State Univ. 1991.**

**Yoo, S.-C. "Turbulence Drag Reduction by Wall Modification" Masters Project Report, Dept. Mech. Engr. Mich. State Univ. 1990.**

**Hamilton, D. and Hofbauer, H., "Measurement of Turbulent Flow In a Water Channel Using the LIPA Technique With a Phosphor Doping Agent", MS Thesis, Dept. Mech. Engr. Mich. State Univ. 1991.**



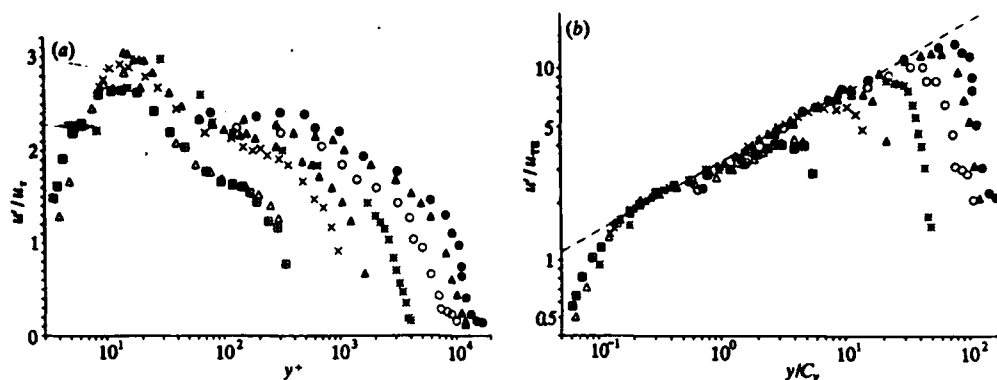


Figure 10. (a) The rms streamwise fluctuation ( $u'$ ) distributions over a wide range of Reynolds numbers, normalized using  $u_{\tau}$  and  $y/y_{\tau}$ .  $\square, \times, \Delta, R_{\theta} = 1010, 2870$  and  $4850$  (Klewicky & Falco 1990);  $\triangle, R_{\theta} = 1340$  (Purtell *et al.* 1981);  $\ast, R_{\theta} = 8000$  (Klebanoff 1955);  $\circ, \Delta, \ominus, R_{\theta} = 18300, 28600$  and  $39000$  (Petrie *et al.* 1990). (b) The rms streamwise fluctuation ( $u'$ ) distributions over a wide range of Reynolds numbers, normalized using  $u_{\tau}$  and  $C_y$ . Symbols are the same as in figure 10a.

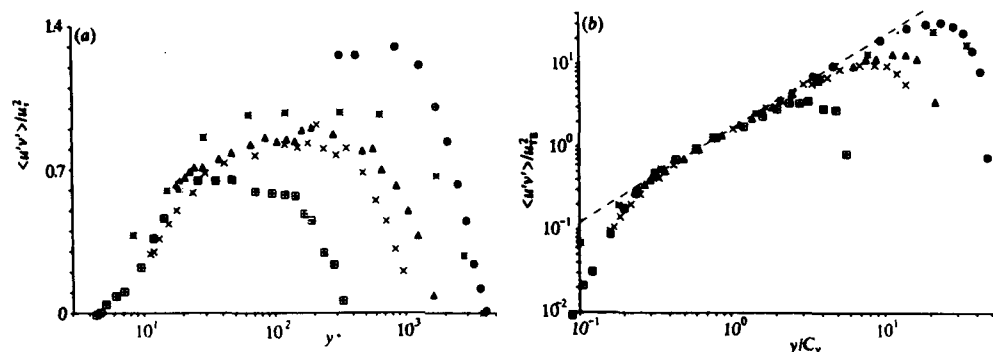


Figure 11. (a) The Reynolds stress  $\langle u'v' \rangle$  distribution over a factor of 15 in Reynolds number, normalized using  $u_{\tau}^2$  and  $y/y_{\tau}$ .  $\square, \times, \Delta, R_{\theta} = 1010, 2870$  and  $4850$  (Klewicky & Falco 1990);  $\ast, R_{\theta} = 8000$  (Klebanoff 1955);  $\ominus, R_{\theta} = 14500$  (Bradshaw & Morrison 1986). (b) The Reynolds stress  $\langle u'v' \rangle$  distribution over a factor of 15 in Reynolds number, normalized using  $u_{\tau}^2$  and  $C_y$ . Symbols are the same as in figure 11a.

again we see that the overlap region (as defined by the law of the wall for the mean flow) is much better accounted for by these length and velocity scales. In addition, the fully turbulent portion of the boundary layer is also very well accounted for. A universal power law relation also exists for the Reynolds stress, over approximately the same range as found for rms  $u$ . The power law region is fitted by

$$\langle u'v' \rangle / u_{\tau}^2 = 1.69(y/C_y)^{1.13}.$$

The collapse in the near wall region, with about the same accuracy as achieved using wall variables, is again suggesting that the  $\tau_w$  influence is as important as the wall scales to within a few viscous units from the wall. The fact that both the rms  $u$  and  $\langle u'v' \rangle$  distributions, which are significantly different in form (when normalized by the classical wall coordinates), can be collapsed by the  $\tau_w$  scales from the wall region through the fully turbulent region (where the wall scaling fails) suggests the importance of the  $\tau_w$  to boundary-layer dynamics.

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